SOME ASPECTS OF EXOPLANETS DETECTION WITH THE TRANSIT METHOD

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1. Introduction

The transit method has recently gained importance among the various methods currently being employed - or discussed - for the detection of extrasolar planets. This is due to its potential to allow the detection of small to moderate size planets in the near future, and to eventually deliver reliable statistics on the abundances of these planets. But also for massive planets, the transit method has recently gained acceptance for the detection of short-periodic giant planets similar to 51 Pegasus.

The transit method makes use of the simple fact, that a planet passing in front of its central star will cause a small, temporal drop in the star's brightness. This method is also known as the 'photometric', 'occultation' or 'eclipse' method - under this last name it was first mentioned by Struve (1952). The first detailed development of the transit method was performed by Rosenblatt (1971). He worked out the shapes of the expected transit amplitudes, and of the minute color changes that are expected from the passage of a planet across a stellar disk. It was soon realized, however, that Rosenblatt was too optimistic with his estimates about the detectability of exoplanets with this method. This situation was corrected by Borucki and Summers (1984), who derived realistic detection rates. The probability that a large outer-orbit giant planet (like Jupiter in the Solar System) is aligned correctly to cause transits - the orientation of the planetary system is *not* known - is very low, on the order of 10^{-3}. This led Borucki and Summers to the conclusion, that several 10^4 stars need to be observed simultaneously with 0.1% precision, which may be "feasible but difficult" from ground based telescopes, and consequently led to proposals for space-based detection systems. Another approach was developed by Schneider and Chevreton (1990), who studied the suitability of observations of eclipsing binary systems, under the assumption that the angle between the planetary plane and the binaries' plane is very small (and hence the angle between the planetary plane and the line of sight to the observer is also very small). A particularly appealing binary system for transit observations was found in CM Dra (Schneider and Doyle, 1995), which has been the subject of an observing campaign by the 'TEP network' for several years (Doyle et al. 1996; Deeg et al. 1997, 1998a).

The recent increase in interest in the transit method is due to two reasons: One has been the unexpected discovery of inner-orbit giant planets in 1995. These should be relatively easy to detect through transits unless they are very rare: Their large size (causing big transit amplitudes) and close, short-periodic orbits (with probabilities of several percent to be aligned right, and causing frequent transits) make them ideally suited for ground based survey programs. The other reason has been the approval of a space mission that will perform a search for planetary transits, in the form of the COROT satellite project (Deleul et al. 1997; Schneider 1997).

For general overviews about the transit method we refer to Borucki and Summers (1984), Hale and Doyle (1994), and Deeg (1997), where detection probabilities and photometric requirements are given. Therefore, in this contribution only some further aspects of the transit method will be outlined.

2. Color Variation in Planetary Transits

Planetary transits will cause characteristic color variations, which are due to the planet transiting across regions with varying colors on the stellar disk (this is due to limb-darkening being color dependent). This was already elaborated by Rosenblatt (1971), who titled his paper on the transit method 'A two-color Photometric Method for Detection of Extra-Solar Planets'. Since colors are measured by subtraction, or comparison, of transits measured simultaneously in different color-bands, reliable color information can only be acquired from transits with amplitudes larger then about 6-10 times the photometric noise. This limits the acquisition of the color signature to transits by larger planets. For this reason, most observing programs employing the transit method have chosen to forego the acquisition of color information. The color information can however be decisive about the true nature of a temporal light-drop in an observed lightcurve. In ground-based observations, light-drops may result from a variety of factors, such as atmospheric transparency and differential extinction variations. But for space-based observations as well, intrinsic stellar brightness variations may be mistaken for transits. Such variations may be emitted either by the program star itself, or by a faint background star, which may even have strong variability but is confused with the program star.

For the confirmation of the planetary nature of an observed 'transit candidate', at least two further transit observations would be needed if measurements have been taken in one color only. With reliable color-information however, a single transit observation may be sufficient to be confident about the detection of an extrasolar planet. Even with color-information, there may however still be ambiguities about the nature of a planetary transit: it may be possible to mistake transits by terrestrial planets around a foreground star with a giant-planet transit across a confused background star. In the case of a binary target, it may also be possible to confuse a terrestrial planet transiting the primary star with a giant planet transit across an unseen secondary (Schneider, 1997).

In any case, the ability to ascertain planetary detection from *one* transit is especially useful for observing programs where is not feasible to follow up a planetary candidate for 3 transits. For this reason, it has been decided for the COROT satellite project, where observing time is limited to 5 months in each field, to include a chromatic disperser in the lightpath. The disperser will allow the acquisition of color information in 2 or 3 bands, additionally to the acquisition of the total flux variation. This addition of color-information will extend COROT's discovery space of massive planets ($\gtrsim 5R_E$) significantly towards longer-periodic orbits, and detections of planets within the habitable zone may be possible.

3. Detection of Moons and Planetary rings

Though it has been realized for a while that the presence of third bodies can disturb the periodicity in the arrival times of planetary transits, it were recent contributions by Sartoretti & Schneider (1998) which showed the use of the transit method for the detection of planetary rings, or of massive planetary moons. These bodies may be detected through deviations from the normal transit *shape*, or by deviations from the strict periodicity of a transits. An opaque planetary ring, for example, may cause a symmetric transit with a step-wise ingress and egress, whereas a moon large enough to cause an observable contribution to the light-loss in a transit would cause stepped, but asymmetric transit shapes. Furthermore, a moon, even if undetectable in the transit shapes, will cause the associated planet to be either leading or trailing the planet-moon barycenter, thereby causing deviations in the *time* of the transit from the strict periodicity with the planet's orbital period. In the Earth-Moon system, for example, the barycenter is offset from the geometrical center of the Earth by 4660 km, causing the Earth's center to lead or trail the barycenter by up to 2.6 minutes on its path around the Sun. Similarly, a system consisting of Saturn and its heaviest moon Titan would cause shifts in transit times up to 30.5 seconds. Such time differences would be easily recognizable, once at least 3 transits have been observed.

4. Reflection Photometry: Transits behind the Central Star

It may be attempted to observe the periodic varying brightness of the reflected light from an extrasolar planet (Fig. 1). The reflected flux, F_r that is received from a planet is given by:

$$\frac{F_r}{F_*} \approx 1/4\ \kappa \left(\frac{R_p}{a_p}\right)^2 (1 - cos\alpha)$$

where F_* is the star's flux, R_p and a_p are the planet's radius and half axis, κ is the planet's albedo, and α is the angle between the observer, the central star and the planet. Since F_r is varying only slowly, with the orbital period of the planet, it is very hard to detect its contribution, and attempts to detect the reflected flux from the known extrasolar planets have not been successful. If the reflecting planet happens to transit *behind* the central star, though, the reflected light will disappear abruptly, and cause a brightness variation of

$$\frac{\Delta F_r}{F_*} \approx 1/2\ \kappa \left(\frac{R_p}{a_p}\right)^2$$

(dashed line at $\pi/2$ in Fig. 1). A planet with such 'back transits' would of course also undergo transits in front of its star at $\alpha = 0, \pi, ..$, where it is causing a brightness variation of $\Delta F/F \approx (R_p/R_*)^2$.

Since generally $R_* << a_p$, the frontal transits cause much larger brightness variations then the back transits, where the reflected light disappears. The back transits can only be expected to be observable for the case of inner-orbit giant planets, where the brightness variation would be on the order of $\Delta F_r/F \approx 10^{-4}$, whereas the variation from a frontal transit would be on the order of $\Delta F/F \approx 10^{-2}$. For these planets, the detection of back-transits would however be a useful diagnostic tool: With R_p being known from the observation of front-transits, a back transit could allow the derivation of the planets's albedo. Further, if back-transits could be observed in several colors, even the planet's color may be deduced.

5. Transits and Minimum Timing in Binary Systems

Transits by planets around close binary systems are of particular interest, since detection of planets in binary systems is inaccessible by the radial

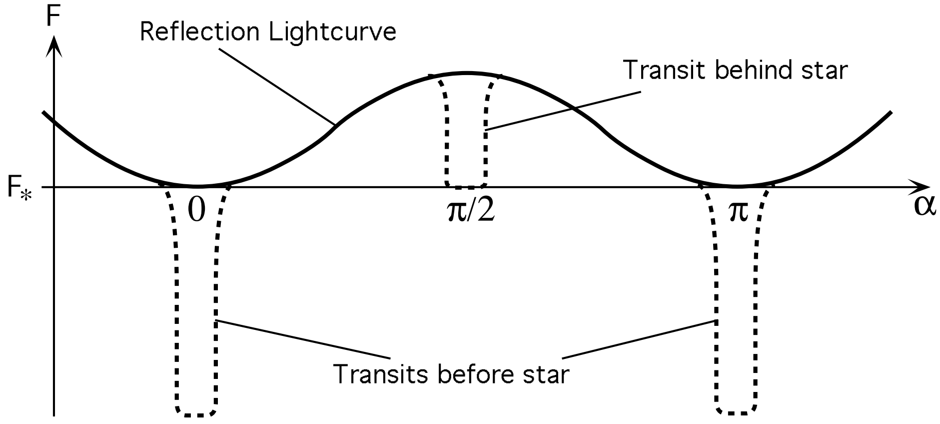

Figure 1. Lightcurve of a star with a reflecting planet (solid line). F_* is the flux from the star without a planet. The horizontal axis (α) is the phase of the planet, given by the angle between planet, star and observer. Dashed lines indicate front and back transits. Note that the depth of the front transits is orders of magnitudes larger then that of the back transits.

velocity method. In the case of eclipsing binaries there is also a high probability, that the planetary plane is aligned to produce transits, and that these transits may display unusual transit shapes (see for examples in Deeg et al., 1998a), which may allow certain detection by a single transit. A 'by-product' of transit searches involving eclipsing binaries is also the possibility to detect periodic changes in the eclipse minima times, which would be indicative of a third body in the system, with at least giant-planet masses (Doyle et al, 1997). A recent announcement by Guinan et al. (1998) that such a periodic change with an amplitude of 18 seconds has been found in the CM Dra system was however invalidated by data taken by the TEP group (Deeg et al, 1998b), which did not show any periodic variations down to much smaller amplitudes.

6. Conclusion

The transit method has undergone several additional developments which have extended its scope and will ascertain its increased use in the next years. Especially notable is the fact that transits may not only searve as a means to *detect* planets, but also to *analyze* them. Through transits we may learn about the presence of moons, planetary rings, and obtain planetary surface colors. Spectroscopic observations of transiting planets may even allow an analysis of their atmosphere for signs of biological activity (see Schneider 1994). The development of a space-based misison in form of the Corot project will lead to the first relibable statistics on the presence of inner-orbit heavy-Earth ($\gtrsim 2R_E$) planets. Further space missions with larger coverage and greater senitivity, such as the Kepler proposal (Borucki et al., 1997) may then one day lead to a reliable estimate of the number of Earth-sized, and of habitable planets in the Universe.

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